Experimental Thermal and Fluid Science 67 (2015) 70–74

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Toward enhancement of water vapour condensation using wettability gradient surface

F.M. Mancio Reis, P. Lavieille, M. Miscevic *

Université de Toulouse, UPS, INPT, LAPLACE (Laboratoire Plasma Conversion d'Energie), 118 route de Narbonne, F-31062 Toulouse, France
CNRS, LAPLACE, F-31062 Toulouse, France

ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form 24 October 2014
Accepted 1 November 2014
Available online 18 November 2014

Keywords:
Contact angle
Heterogeneous wettability
Hydrodynamic model
Contact angle hysteresis

ABSTRACT

This paper focuses on the behaviour of a liquid droplet on the surface of a treated solid substrate. We deal with the use of surface tension forces induced by heterogeneous wettability to allow the removal of the droplet. Our main aim is to present a new model able to predict the motion of a droplet of known volume along a wettability gradient taking into account the contact angle hysteresis: a key parameter in the dynamics of the droplet.

1. Introduction

Two-phase systems are among the most efficient for the transfer large heat fluxes. They are based on the latent heat associated to a change of state of matter, i.e. latent heat transition such as vapour condensation [10,7]. Even though two-phase systems are known to be effective, their control under microgravity conditions is not yet fully completed, the removal of the dispersed phase remaining hard to control. On ground environment, similar difficulties can be encountered in miniaturized devices if gravitational forces become negligible compared to surface tension forces. To avoid this phenomenon many studies have been developed on superhydrophobic surfaces where the surface energy released upon drop coalescence leads to a out-of-plane jumping motion (see for instance [1,8]. A surface tension force induced by heterogeneous wettability appears also as an interesting technique to drive the dispersed phase. In this regard it is considered that heterogeneous wettability of a solid surface enables the mechanical non-equilibrium of the drop embryos forming at the wall. This paper focuses on the modelling of the behaviour of a liquid droplet over a solid substrate. Pinning the contact line, i.e. contact angle hysteresis, hereafter called CAH, has proved to be a major experimental and theoretical problem. Experimentally, CAH tends to restrain the contact line and hence the motion of the droplet, either on an inclined plate or on one with a wettability gradient. Theoretically, CAH has been neglected in studies about wettability gradients but recently found to be a major phenomenon deserving attention. Therefore, we developed a dynamic model that actually takes into account the CAH. Firstly, the dynamic model with CAH is presented comparing the results with experimental data found in the literature. Secondly, the different treatments allowing such behaviour of the droplet and the first performance of such gradient on a condensation test chamber are presented.

2. Dynamic model with contact angle hysteresis

The contact angle of a droplet on a wettability gradient surface, with or without tilted plate surface (with an angle of α compared to the horizontal) has been widely studied in the literature both experimentally and theoretically [3,2,11,9]. The most common approach is based on hydrodynamic theory consisting in the balance of the driving force, related to both wettability gradient and gravity in the case of $\alpha < 0$, with the viscous force near the contact line, related to the velocity of the droplet. The dynamic model presented below is based on four main hypotheses:

- the droplet maintains its spherical cap shape during the movement, the dynamic contact angle is then the same at all points on the triple line for a given position on the substrate. This hypothesis has been verified experimentally by several authors [9],

* Corresponding author at: Université de Toulouse, UPS, INPT, LAPLACE (Laboratoire Plasma Conversion d'Energie), 118 route de Narbonne, F-31062 Toulouse, France.

E-mail addresses: felipe.mancio@laplace.univ-tlse.fr (F.M. Mancio Reis), pascal.lavieille@laplace.univ-tlse.fr (P. Lavieille), marc.miscevic@laplace.univ-tlse.fr (M. Miscevic).

http://dx.doi.org/10.1016/j.expthermflusci.2014.11.001
0894-1777/

- the volume of the droplet remains constant,
- the inertia term is ignored.

Finally, the momentum balance projected on the x-axis, tangent to the solid wall is:

$$F_\theta(x_G, t) + F_\mu(x_G, t) - mg \sin \alpha = 0 \quad (1)$$

where F_θ is the driving force and F_μ is the viscous force.

2.1. Driving and viscous forces

The driving force due to the gradient of the static contact angle without taking into account the CAH, is well described in the literature [5,2,9]:

$$F_\theta(x_G, t) = \gamma_{lv} R(x_G, t) \int_0^{2\pi} (\cos \theta_s(x) - \cos \theta(x_G, t)) \cos \phi \, d\phi \quad (2)$$

with $x = x_G + R(x_G, t)\cos \phi, x_G$ corresponds to the abscissa of the centre of mass of the droplet, γ_{lv} is the vapour–liquid surface tension, θ_s is the static contact angle defined by the wettability of the substrate, θ is the dynamic contact angle, ϕ is the azimuth, and $R(x_G, t)$ is the footprint radius of the drop at the position of the centre of mass x_G:

$$R(x_G, t) = \sin \theta(x_G, t) \left(\frac{3V}{\pi}\right)(2 - 3\cos \theta(x_G, t) + \cos^3 \theta(x_G, t))^{-1/3} \quad (3)$$

The hypothesis of a spherical cap shape implies that the cohesion force of the liquid–vapour interface is much higher than the driving force related to the wettability gradient. So, the model is valid if the volume of the droplet satisfies the following condition,

$$F_\theta(x_G, t) \ll 4\pi\gamma_{lv} R(x, t) \frac{1 - \cos \theta(x, t)}{\sin \theta(x, t)} \quad (4)$$

which has been verified for the conditions presented in this paper. As presented above the main point of this section is to present a dynamic model describing the motion of a liquid droplet on a wettability gradient which takes into account the CAH. First, let us consider a drop placed on an inclined plate. Because of CAH, it starts sliding when the contact angle at the front reaches the advancing contact angle and the contact angle at the rear decreases to the receding contact angle:

$$\begin{cases} \theta_{rA} > \theta_{rear} \\ \theta_{front} > \theta_{aB} \end{cases} \quad (5)$$

In-between the front and the rear of the droplet, the contact angle is within the contact angle hysteresis. Thus, locally, the contact angle is not the static contact angle (referring to the angle that a static interface would have at a given location on a horizontal substrate). In the following, this contact angle will be called "equilibrium contact angle".

Nevertheless, with small droplets (less than 1 μL) the gravitational force is less than the capillary forces and the droplet remains with its spherical cap shape ($\theta_{rear} = \theta_{front} = \theta$), which implies that small droplets do not slide on inclined plates due to CAH. Likewise, a droplet on a surface energy gradient is subjected to the same constraints regarding the hysteresis effect. The wettability gradient allows to satisfy relation (5) while simultaneously keeping the same contact angle along the periphery of the droplet, and so:

$$\theta_{rA} \geqslant \theta \geqslant \theta_{aB} \quad (6)$$

Therefore, we integrated the local expression of the driving force (Eq. (2)) assuming a continuity of the equilibrium contact angle (i.e. the local contact angle that should have a droplet when at the limit of moving on an inclined substrate) between the front and the rear of the droplet. Because the drop is small, a linear cosine from the advancing contact angle at the front to the receding contact angle at the rear of the droplet has been defined as shown in Fig. 1. A small droplet subjected to a surface tension gradient can move regardless of the CAH, and the driving force is, as predicted, attenuated by the hysteresis effect assuming a linear cosine of the static contact angle, Eq. (2) becomes:

$$F_\theta(x_G, t) = \gamma_{lv} R(x_G, t) \int_0^{2\pi} (a(x_G, t)x + b(x_G, t)) \cos \phi \, d\phi \quad (7)$$

Because the dynamic contact angle remains the same around the periphery of the droplet, which is approximated to the equilibrium contact angle at the centre of mass of the droplet [2,9], the integration of the second term is zero. The parameter $a(x_G, t)$ represents the variation of the cosine of the contact angle along the droplet:

$$F_\theta(x_G, t) = \frac{\gamma_{lv} R(x_G, t)\pi}{2} [\cos \theta_a(x_G + R(x_G, t)) - \cos \theta_r(x_G - R(x_G, t))] \quad (8)$$

Ultimately, Eq. (8) shows the link between the driving force and CAH assuming that (see Fig. 1 for notations):

$$\begin{cases} \theta_a = \theta_s + \frac{CAH}{2} \\ \theta_r = \theta_s - \frac{CAH}{2} \end{cases} \quad (9)$$

The drop in motion is subjected to wall shear stress that generates a viscous force directly related to the droplet velocity. Brochard [2] and then Subramanian et al. [11] developed two viscous force models. They both considered the lubrication theory and a Poiseuille type velocity profile in the droplet. The difference between the two viscous force models remains in the geometrical configuration chosen. Unlike Brochard [2], Subramanian et al. [11] took into account the curvature of the drop by relating the footprint radius, the contact angle and the height of the drop. In the present paper, the Subramanian viscous force was chosen:

$$F_\mu(x_G, t) = -6\pi\mu U(x_G, t) R(x_G, t)[f(\theta, 1 - \epsilon) - f(\theta, 0)] \quad (10)$$

with

$$f(\theta, \xi) = -[\cot \theta(x_G, t) \, ln(\sqrt{\csc^2\theta(x_G, t) - \xi^2} - \cot \theta(x_G, t)) + \sqrt{\csc^2\theta(x, t) - \xi^2} - \cot \theta(x_G, t)] \quad (11)$$

The slip length L_s, which represents the length at which the physical phenomena of macroscale are no longer valid, is directly related to parameter ϵ by the relation $L_s = \epsilon \, R(x_G, t)$. The value of L_s has been

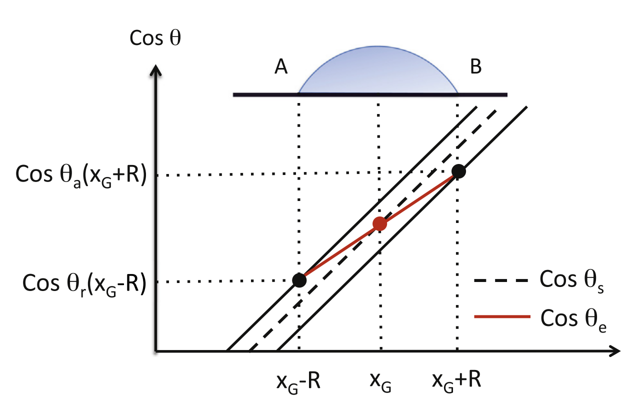

Fig. 1. Consideration of a linear cosine between the advancing and receding contact angles.